NEHRP Program FY-2007
External Grant Award Number 07HQGR0090

ANTON ESCARPMENT
PALEOSEISMOLOGIC INVESTIGATION
WASHINGTON COUNTY, COLORADO

Bill Ritter Jr., Governor
State of Colorado

COLORADO
DEPARTMENT OF NATURAL RESOURCES

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March 31, 2010

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ABSTRACT*

The Colorado Geological Survey (CGS) recently completed a multi-year field investigation of the Anton escarpment on Colorado's eastern plains to determine if this linear, 135-km-long, 24-m-high feature is seismogenic in origin. We dug 600 meters of trenches augmented by borehole cores and a seismic refraction survey. Sediment samples were dated using luminescence and radiocarbon techniques. We used a high-resolution stratigraphic framework to evaluate the nature of geomorphic evolution on and adjacent to the escarpment.

We found no evidence of faulting. The trenches exposed a succession of predominantly eolian units overlying gravels of the Miocene Ogallala Group. The upper escarpment contains late Pleistocene sand dune (70 to 38 ka) and loess and sand sheet (29 to 16 ka) sediments. The flanking low area is floored by eolian loess and sand layers (Pliocene to middle Pleistocene) with strong calcic paleosols. These are overlain by a zone of polygonal sand wedges and other periglacial features (27.5 to 16.5 ka), sand sheet and playa deposits (16.5 to 12.5 ka), and loess with humic paleosols (12.5 to 6.4 ka).

The younger (post-29 ka) units form discontinuous sediment bodies that overlie gullied, bowl-like, or flat-bottomed erosion surfaces with up to 27 m of paleotopography. The older units appear to be continuous beneath the escarpment face. We interpret that the Anton escarpment is not a late Quaternary paleoseismic feature, but instead was created by paleowinds. It marks a linear interface between an extensive, late-Pleistocene plateau of thick loess and sand deposits dominated by eolian aggradation and a contemporaneous, adjacent, topographically low plain dominated by wind erosion and partial infill.

** Abstract is revised from Noe and others (2008)*

INTRODUCTION

In 1970, only eight suspected Quaternary faults were recognized in Colorado (Scott, 1970). The number of verified or suspected Quaternary faults in the state has since risen to more than 90 (Widmann and others, 2002) as a result of investigations by the Colorado Geological Survey (CGS), U.S. Geological Survey (USGS), U.S. Bureau of Reclamation (USBR), and a number of private consultants. Nearly all of these young faults are found in the mountains and plateaus in the western 2/3 of the state (**Figure 1**).

The Great Plains region of eastern Colorado is considered by some geoscientists as tectonically quiescent since the Laramide orogeny (e.g., Leonard and Langford, 1994). Important exceptions include the Cheraw fault in southeastern Colorado (**Figure 1**) (Scott, 1970; Kirkham and Rogers, 1981; Crone and others, 1997) and the Meers fault in southwestern Oklahoma (Crone and Luzka, 1990). Crone and others documented surface-rupturing events at the Cheraw fault of 8 ka, 12 ka, and 20 to 25 ka based on a trenching study, with vertical offsets of 1.6 and 2.7 m for the last two events. In contrast, other studies by the USGS identified fault-like geomorphologies that could be attributed to non-tectonic origins (Machette and others, 1998).

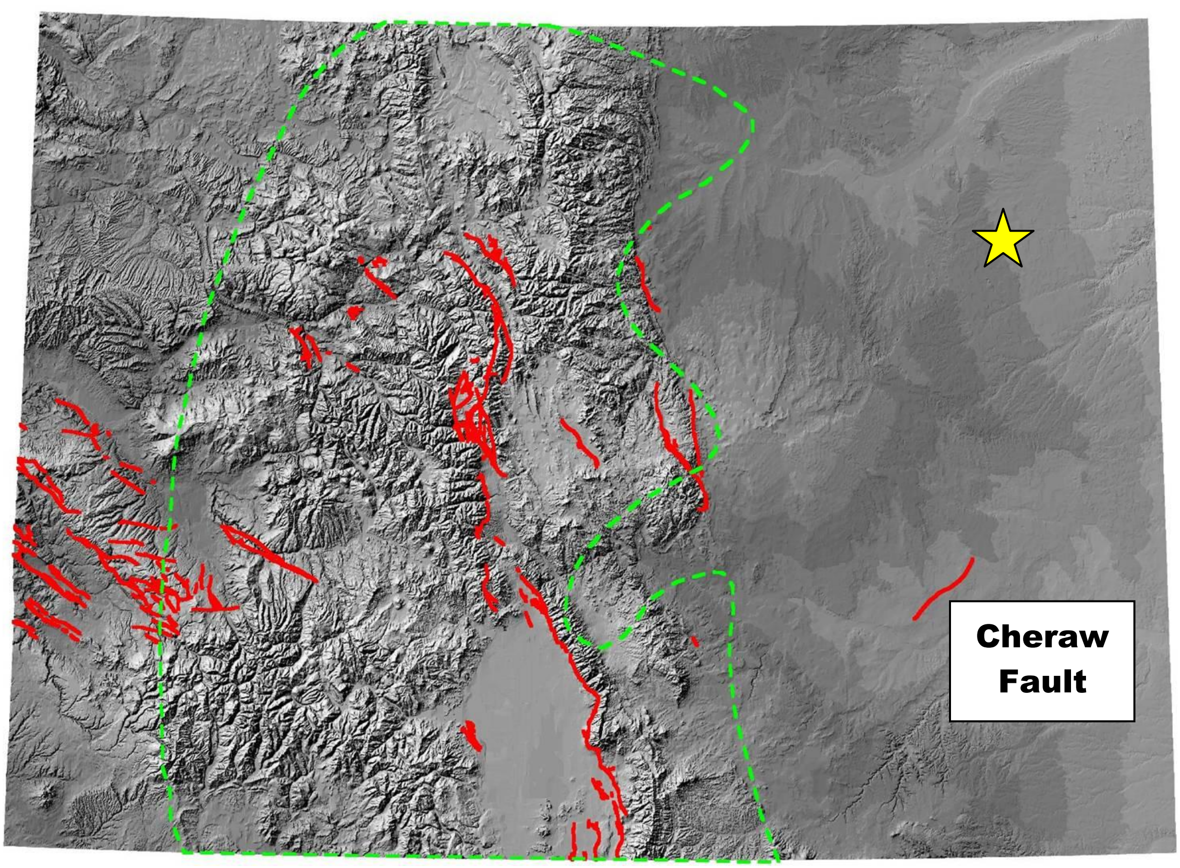

Figure 1. Draped-DEM GIS image of Colorado showing the location of known Quaternary faults (red) and area of high gravity associated with the core of the Southern Rocky Mountains (dashed green line). Anton study site marked by yellow star.

The discovery of young faulting in the generally stable interior of the mid-continent is cause for a re-evaluation of the faulting history and earthquake potential there. In particular, this calls for the identification, verification, and characterization of other potentially tectonic features.

Since 2003, the CGS used GIS and three-dimensional imagery to identify potential Quaternary faults within Colorado's Great Plains. The most likely candidate is a striking linear feature that we informally refer to as the Anton escarpment (after nearby Anton, CO, pop. 14) (**Figure 2**).

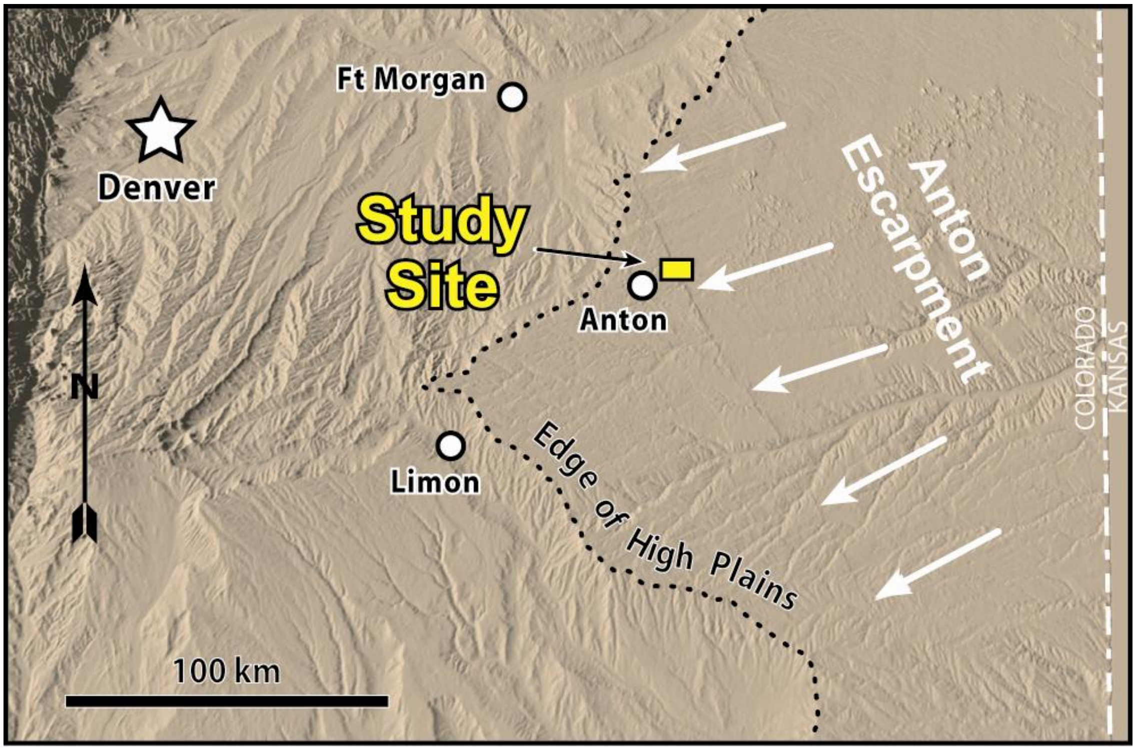

Figure 2. Draped-DEM GIS image of eastern Colorado showing the Anton escarpment (white arrows), about 160 km east of Denver, Colorado.

The escarpment is at least 135 km long and 20 to 30 m high (Matthews, 2004). It faces northeast and separates a loess-covered upland to the west from a gravel and sand-covered lowland to the east (**Figure 3**). McGovern (1964) considered the escarpment to be the edge of a regional loess sheet, oriented along the prevailing northwest-to-southeast wind direction. Matthews (2004) postulated a tectonic origin for the escarpment. He noted features suggestive of left-lateral slip, including long-distance linearity and the possible presence of left-stepping segments, left-lateral stream deflections, and a potential associated Reidel-shear escarpment.

Using the surface-rupture length– moment magnitude correlations of Wells and Coppersmith (1994), a hypothetical maximum M 7.6 earthquake event was modeled for the escarpment as part of recent FEMA HAZUS assessments by CGS. HAZUS-MH indicates a total economic loss of $12.8 billion, including $3 million in Denver.

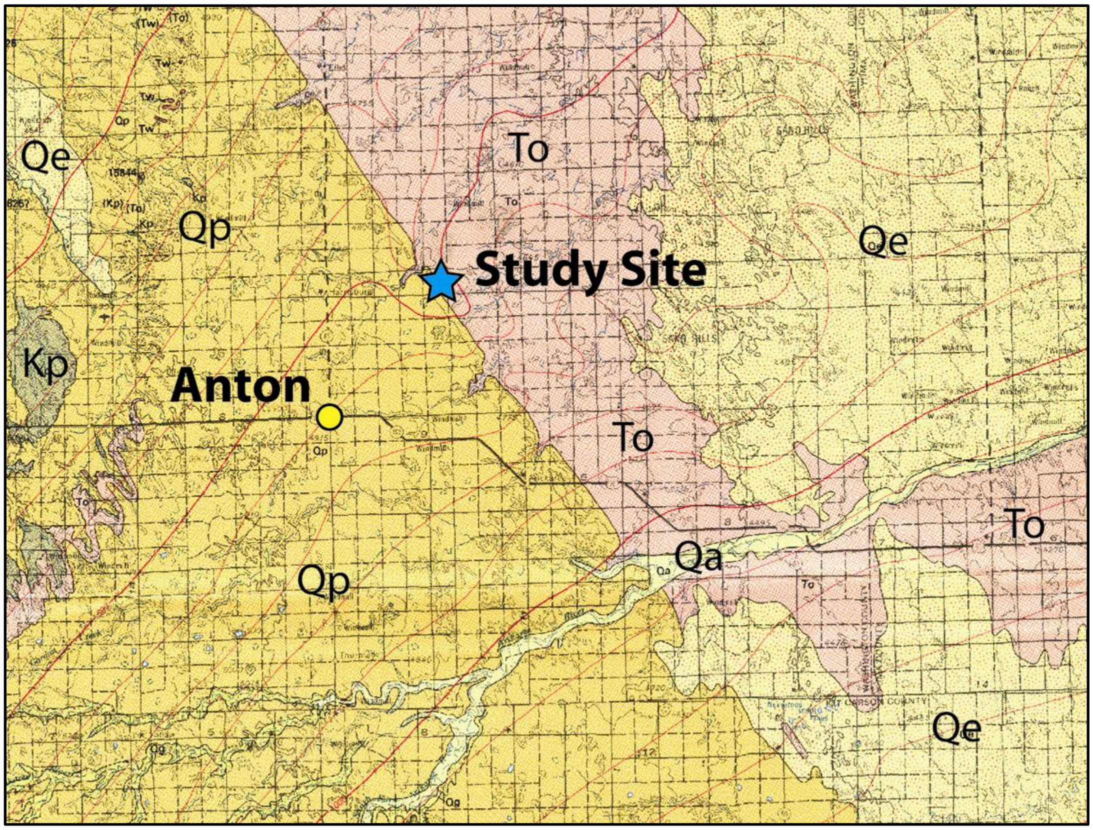

Figure 3. Geologic map of the study area (Sharps, 1980). The Anton escarpment runs along a northwest-southeast-trending boundary between a Pleistocene loess-capped upland (Qp) to the west and a lowland floored by Tertiary Ogallala Formation (To) and Holocene eolian sand-dune fields (Qe) to the east.

PREVIOUS INVESTIGATIONS

The CGS first investigated the escarpment in 2004 at the study site location 11 km northeast of Anton. Refraction-seismic and ground-penetrating radar surveys detected no offsets in dense soils or poorly cemented bedrock beneath the slope. No change in depth was observed along the contact between those layers and deeper (shale) bedrock (Geophysica, 2004).

Research trenches were dug in 2004 and 2005. They are informally named the upper and lower trenches, respectively (**Figures 4 and 5**). Each trench was approximately 180 m long.

The 2004 upper trench was excavated in the upper slope (**Figures 5 and 6**). It encountered 20 m of nearly flat-lying sand dune, loess, and sand sheet sediments (units U1 and U2). Those units are late Pleistocene in age (Mahan and others, 2005; Noe, 2005). The escarpment face was found to be erosional and contained a series of filled, Holocene gullies (unit U3) beneath the steepest part of the face. We found no evidence of rupture or faulting in the upper trench.

Twelve boreholes (5.6 to 11.4 m deep) (**Figure 5**) were drilled in 2004 to augment the trenching, and 6-cm-diameter sediment cores were recovered. We correlated stratigraphic marker beds beneath and downhill from the upper trench across a closed playa depression. Several key stratigraphic markers,

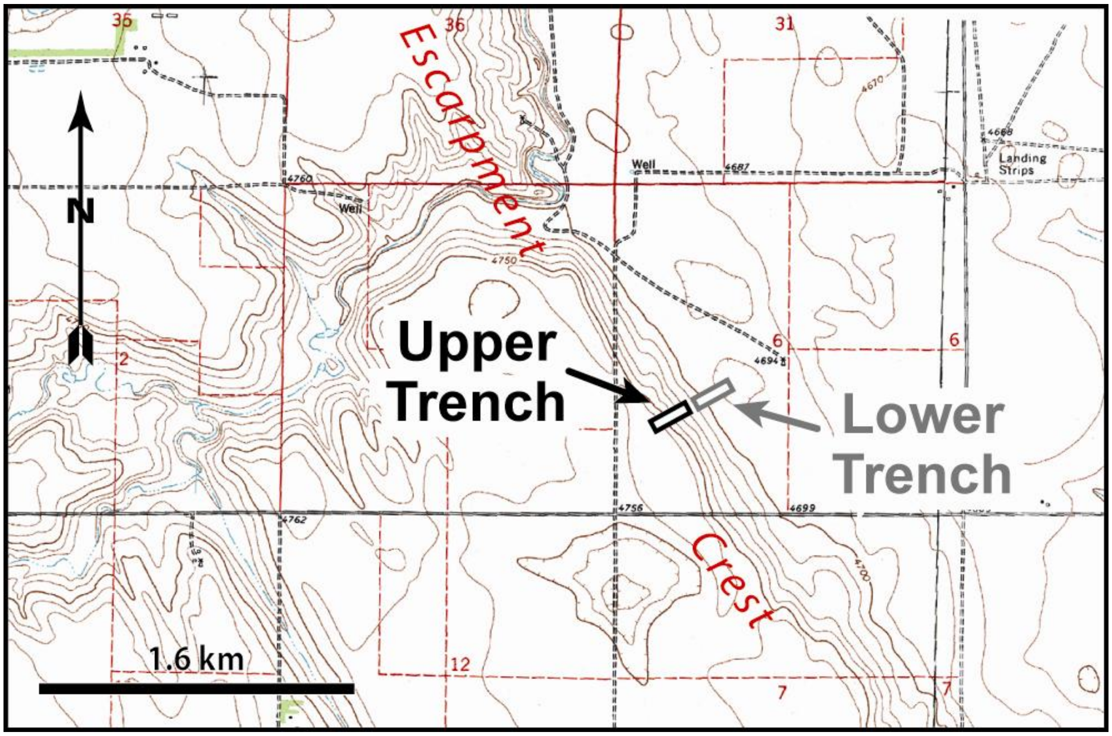

Figure 4. Map of Anton escarpment study area showing the location of upper (2004) trench near the crest of the escarpment and the lower (2005) trench near the toe of the slope.

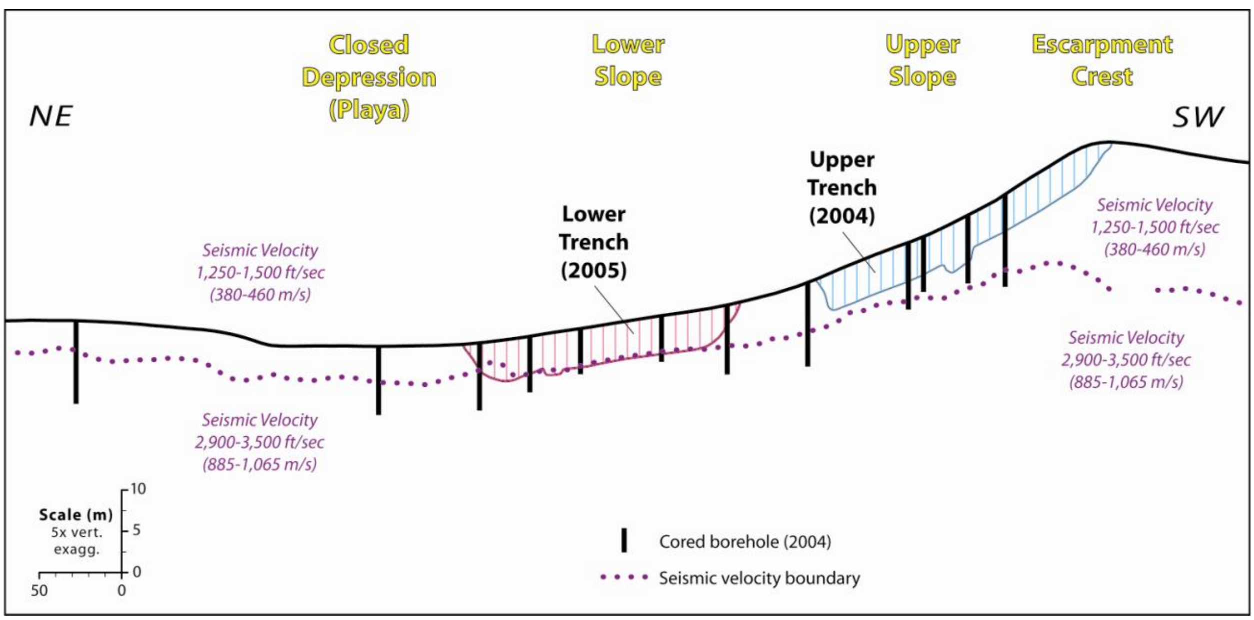

Figure 5. Cross-section of the Anton escarpment study site, looking southeast. This section shows the geomorphology of the escarpment slope, upper and lower trenches, cored boreholes, and a seismic-velocity boundary between unconsolidated surficial deposits and deeper, poorly cemented sediments.

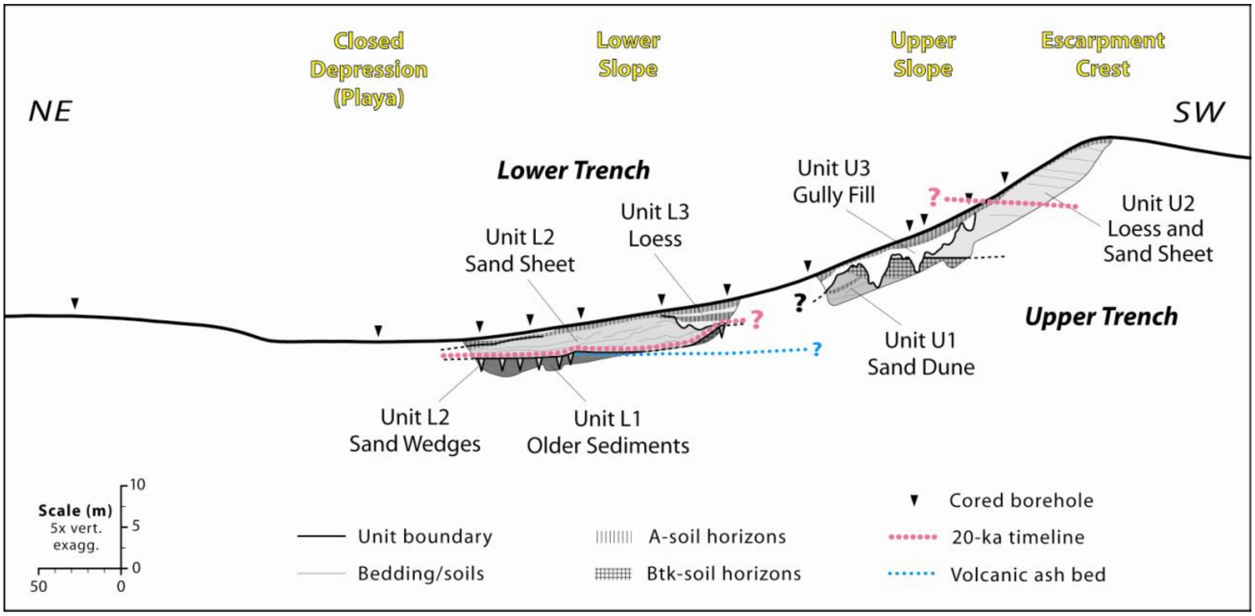

Figure 6. Cross-section of the Anton escarpment study site, with 5x vertical exaggeration, showing general stratigraphic units and soil horizons from the 2004 and 2005 trenching. The view reflects that the southeastern walls of the trenches were logged.

including a volcanic ash bed, were found to be discontinuous (Noe and McCalpin, 2005). We postulated that either faulting or erosional truncated the marker beds.

Based on our 2004 trenching, coring, and regional observations, Wheeler (2005) listed the Anton escarpment in the USGS National Seismic-Hazard Map data- base and assigned it as a Class C feature.

The 2005 lower trench was excavated in the lower escarpment slope (**Figures 5 and 6**) to test the cause of a discontinuous ash bed. It exposed a different stratigraphic succession than the earlier trench. A basal package of older sediments (unit L1), ranging from Miocene(?) to middle Pleistocene(?) age, is partially removed by an erosional unconformity with 4 m of paleotopography. The erosion surface is overlain by coarse, late Pleistocene sand sheet deposits (unit L2). Polygonal sand wedges are found extending into the older sediments below the surface, indicating an extensive permafrost surface. A near-surface, late Pleistocene to early Holocene depression filled with loess and humic paleosols (unit L3) was identified at the western end of the trench. We found no evidence of rupture or faulting in the lower trench.

The two trenches were separated by 50 m. We could not definitively correlate the shallower stratigraphic units between the trenches. However, we correlated a deeper volcanic ash bed that was found in the lower trench and in a borehole core beneath the downhill end of the upper trench (**Figure 6**).

Initial Interpretations from 2004-2005 Trenching

We established two timelines between the two trenches in order to assess potential offsets. The first is a volcanic ash bed, encountered in cores and lower trench (**Figure 6**). This bed is near horizontal beneath the lower slope at depths of 4 to 7 m (13 to 23 ft). Its geochemistry and glass-shard characteristics best match an ash bed from the Pliocene Glenns Ferry Formation in eastern Idaho, with an inferred age of 3.7

to 3.0 ma (E. Wan, USGS Tephrachronology laboratory, personal communication, 2008). The continuity and horizontality of this ash bed between the trenches precludes any normal faulting in that part of the slope. The ash bed and bounding strata are more continuous than the overlying Quaternary units. The ash bed is truncated to the east by the erosion surface at the base of unit L2.

The second timeline is based on age-dating results from over 20 radiocarbon and luminescence samples from the two trenches. A 20-ka timeline appears to have significance for illustrating the first appearance of the escarpment (**Figure 6**). This timeline marks the base of coarse sand sheet deposits in both trenches. In the lower trench, it is represents the periglacial sand wedges (27.5 to 18 ka) and, by inference, the erosion surface at the top of the wedges. In the upper trench, the 20 ka timeline lies within a well-defined and possibly disconformable contact between a 29 to 23 ka loess deposit and a 17.5 ka sand sheet deposit.

In **Figure 6**, the 20 ka timelines from the two trenches are at markedly different elevations. In order for them to meet, the paleo land surface represented by the timeline must climb 14 m across a segment of the escarpment slope that was not trenched. The trace of the timeline across this segment (which is missing at least in part because of later erosion) must mark the incipient appearance of the Anton escarpment as a geomorphic and topographic feature.

It is notable that the lower-trench 20 ka timeline occupies a low-lying erosional surface, whereas the upper-trench 20 ka timeline caps a thick (7 m) loess deposit. This implies that two different processes were operating side-by-side during the same time period. Sediment deposition and aggradation occurred in the loess plateau, while erosion and deflation occurred in the adjacent lowland. The escarpment is the boundary between these regions. Our initial findings suggest that simultaneous wind erosion and deposition may have played a major role in the formation and growth of the escarpment.

<u>Results from Nearby Locations</u>

CGS created a cross-section of oil-and-gas well logs that crossed the escarpment about 26 km north of the Anton study site. The section shows that the top of the Dakota Sandstone rises abruptly about 30 m in the vicinity of the escarpment. This indicates a subsurface fault with down-throw to the east. We could not establish any stratigraphic markers that showed fault offset at shallower depths, however.

In the same general location, CGS examined a pipeline trench that was excavated across the escarpment. We documented a sediment- and soil-filled deflation basin, underlain by a heavily rodent-burrowed zone, at the base of the escarpment slope. Unfortunately, we were unable to access the trench walls directly and could not take samples for age-dating. Thus, the evidence for faulting is inconclusive.

NEED FOR PRESENT STUDY

No conclusive evidence of near-surface fault rupturing was found during our initial studies at the Anton site. However, it is possible that we either did not dig deep enough in the thick Quaternary deposits or in the right place. Based on our findings from the 2004 and 2005 trenches, we identified two untested locations at the study site where faulting could occur:

1) <u>Beneath the deepest and lowermost gulley channel</u> (unit U3 in **Figure 6**) in the upper escarpment slope. This coincides with a lateral change in bedding dip between eolian strata on both sides. The rise of the unconformity surface within the 50-m long zone between trenches must involve either erosion or faulting within this zone

2) To the east of the lower trench across a closed playa depression. This playa may represent a graben area, or (because the escarpment face is erosional) its eastern edge may represent a fault line that is not currently exposed. This depression lies along a projected base of the escarpment to the north and south of the study site.

3) A third, distinct possibility is that there is no late Quaternary faulting and that the escarpment is solely the product of wind or water processes.

Our NEHRP grant proposal was geared toward testing these potential faulting sites. It called for trenching the remainder of the escarpment slope and the adjacent closed depression (playa). A high-resolution stratigraphy would be established, encompassing all new and former trenches and cores.

The basic questions to be addressed by the proposed study include the following:

1) *When did the Anton escarpment form and what was the process of formation?*

2) *Are tectonic faults present, and if so, what is the nature of fault movement and timing and magnitude of rupture events?*

METHODOLOGY

CGS excavated two new research trenches at the Anton study site in 2007 under the auspices of this grant (**Figures 7** and **8**). The center trench (113 m long) was dug to link the earlier trenches. The playa trench (213 m long) was dug across the closed depression at the base of the slope. The trenches were benched and excavated to 4.5 to 6 m depths (**Figure 9**) using a large trackhoe.

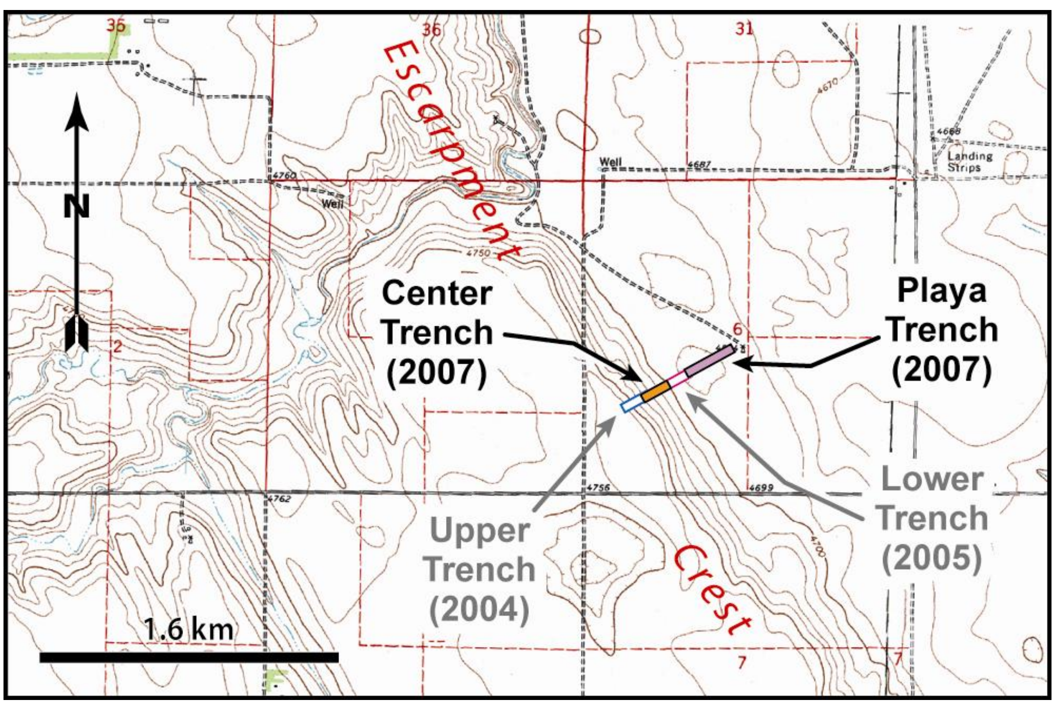

Figure 7. Map of the Anton escarpment study site showing the locations of two new trenches dug in 2007 under the auspices of NEHRP grant 07HQGR0090.

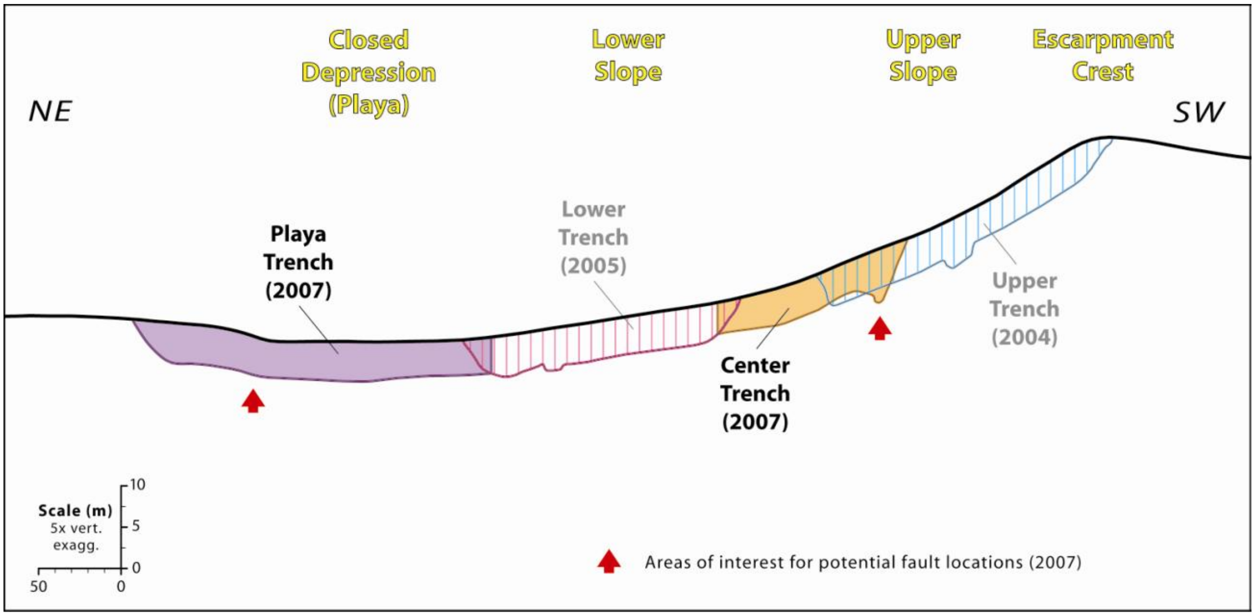

Figure 8. Cross-section of the Anton escarpment study site, looking southeast, showing the locations and overlap of all four trenches along the escarpment slope. Two areas of interest for potential fault locations are shown by the red arrows. These areas were the main targets of our 2007, NEHRP-funded investigation.

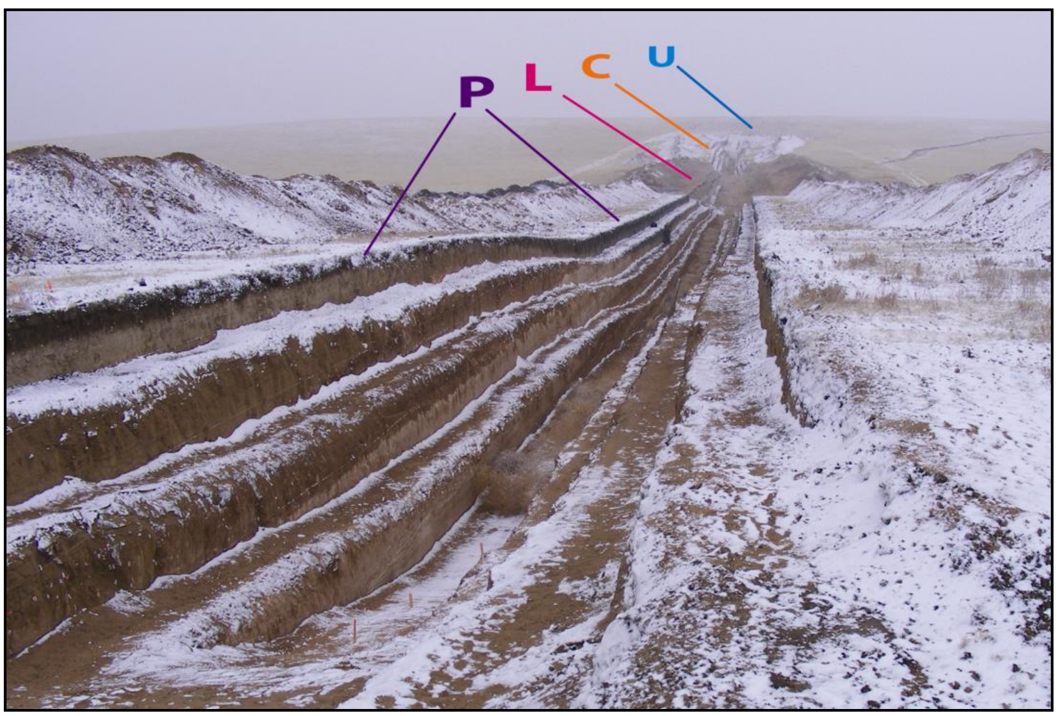

Figure 9. Photograph of the completed trenches at the Anton Study site, looking southwest from a low knoll at the east end of the playa toward the main escarpment slope in background. The locations of the playa (P), lower (L), center (C), and upper (U) trenches are shown.

We scraped and cleaned the trench walls to expose sediments and installed level-line grids. Stratigraphic boundaries were marked using flagging and nails. The southeastern side of the trench walls was logged by sketching the geology on gridded paper at a scale of 1 inch = 1 meter. We used field-investigation practices described by McCalpin (1996). Radiocarbon and luminescence samples were recovered to age-date key strata and, if necessary, to document periods of fault movement. For simplicity, the age-dating results are reported without error variations in approximate 10^3 calendar years (ka) before present.

RESULTS

A simplified cross section of the study site is shown in **Figure 10**. The section is a composite of all four trenches. Certain beds are projected away from the trenches into the subsurface based on correlations from borehole cores. The additional trenching reveals a complex stratigraphy of near-surface deposits beneath the escarpment slope and playa. Using detailed trench-wall logging and over 20 additional age-dates of sediments, we delineated five stratigraphic units of late Pleistocene age (units P1 to P5, **Figure 10**) and three units of Holocene age (units H1 to H3), all atop a basal sequence of older sediments.

The most important finding is that we found no evidence of faulting or rupture in these late Pleistocene to Holocene sediments. In particular, the sediments beneath our two points of interest for potential faulting were intact. This includes the dune sand (unit P2) beneath the lowest filled gully on the upper slope (unit P4) and all of the sediments at the northeastern edge of the playa.

The trenching reveals that there was considerable paleotopography, up to tens of meters, which developed through time. We can trace the formation of the escarpment to a period from approximately 29 to 16 ka. Our interpretation is that the escarpment represents a sedimentological boundary between an area of eolian deposition with negligible erosion (the loess plain to the west) and an area of considerable wind erosion with episodic, depression-filling eolian deposition (the lowlands to the east) (**Figure 3**).

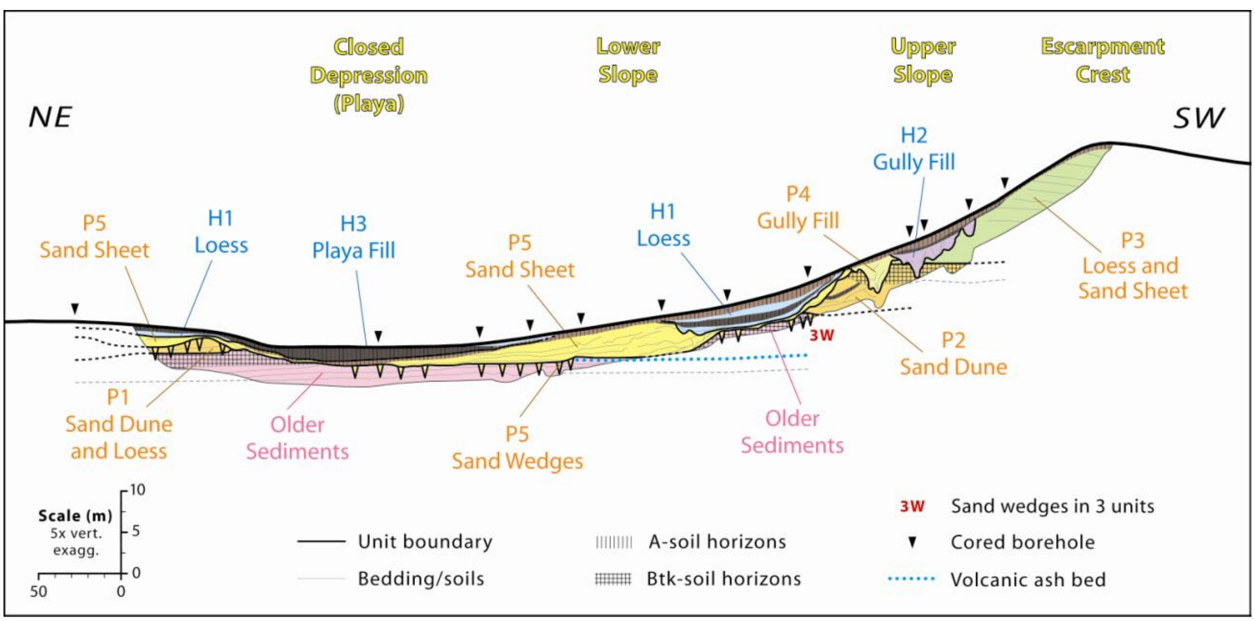

Figure 10. Cross-section of the Anton escarpment study site, looking southeast with 5x vertical exaggeration, showing stratigraphic units and soil horizons from the 2004, 2005, and 2007 trenching.

Depositional History and Escarpment Evolution

Because of complex stratigraphy, the evolution of the Anton escarpment at the study site is best seen by breaking **Figure 10** into a series of cross sections that show interrelated groupings of sedimentary units. In the following section, we describe the units from oldest to youngest. This approach allows us to recognize the timing, distribution, and magnitude of major depositional and erosional events.

Older Sediments. Most of the escarpment face is underlain by older deposits (**Figure 11**). This unit contains a basal gravel (the top of the Miocene Ogallala Group?), overlain by 8.5 m of thin, eolian sand and loess beds of Pliocene to middle Pleistocene age. The previously described volcanic ash bed (3.7 to >3.0 ma, middle Pliocene) lies within the eolian sediment package.

Calcic (Btk) paleosols are found throughout the older sediments. The uppermost 5 m contains heavy (stage III+), welded, calcic paleosols. This soil zone is found in two locations, to the northeast of the playa and beneath the lower to upper slope transition. It is removed by erosion in between. The top of the unit contains small sand wedges and poorly sorted and deformed sediments. The latter features are evidence of permafrost and melting (solifluction) conditions. This is the earliest of three ages of sand-wedge deposits found in this part of the trench (labeled 3W in **Figure 11**). A luminescence sample from the sand wedge has an age of ca. 130 ka (OSL cal yrs), or late middle Pleistocene.

The individual eolian beds in the older deposits are relatively flat-lying, and appear to be partially eroded, with only the lower (Btk) parts of their soil profiles preserved. The internal erosion surfaces are broad and flat. We interpret that this sequence records numerous episodes of eolian deposition, soil formation, and partial erosion by wind deflation. Long periods of time are implied, particularly in the development of the different soil horizons.

The older deposits may extend to the southwest beneath the escarpment crest. There is no evidence that the Anton escarpment existed at this time.

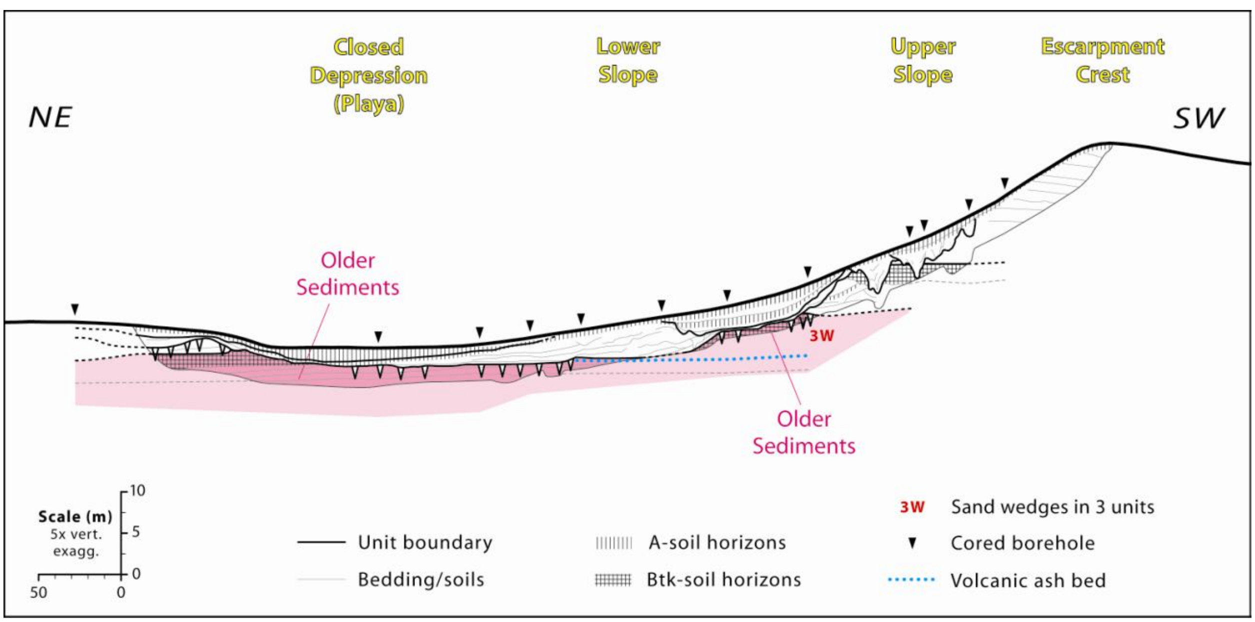

Figure 11. Cross-section of the Anton escarpment study site showing older sediments from the trench (brighter pink) and cores (light pink).

Units P1 and P2. Eolian sand and loess deposits of late Pleistocene age overlie the older sediments in two places (**Figure 12**). Unit P1 is 2 m thick and contains interbedded loess and sand dune deposits. It is located to the northeast of the playa. Unit P2, located beneath the upper escarpment slope, is 6 m thick and contains sand dune and minor sand sheet deposits. These deposits occupy different elevations upon the eroded older sediments. We interpret them to be roughly coeval in age based on similarities of color, pedogenesis, and weathering.

The sediments in both units are relatively dense and well sorted. They contain organic-rich (AB) and calcic (Btk) paleosols. The base of unit P2 contains sand wedges, filled with well-sorted sand, that extend downward 0.5 to 1.5 m into the older sediments. This is the second of three levels of periglacial sand wedges (labeled 3W in **Figure 12**). This indicates that the eolian sands and silts were deposited upon a low-topography surface that contained permafrost and patterned ground.

The top of unit P1 is completely eroded away. The top of unit P2 is partially preserved. The uppermost sediments consist of thin, flat-lying, sand and silt beds with medium to heavy (stage II to III+), welded, calcic and humic paleosols (equivalent to the Gilman Canyon Formation?). We did not age-date unit P1 because of pedogenic alteration. In unit P2, the basal sand wedges and sand sheets to be 70 ka based on luminescence dating. The youngest sediments include an isolated sand wedge (42.5 ka) and a buried humic soil (38 ka) near the eastern edge of the unit. The soil is sloped somewhat parallel with the modern escarpment slope, and is underlain and overlain by structureless, rodent-burrowed sand. We interpret this to be a record of local dune erosion, slope failure, soil formation, and renewed deposition, not a precursor to the modern escarpment. We interpret unit P1 to be a loess field with isolated sand dunes and unit P2 as a sand dune field. They may have existed at slightly different times, or they may have been coeval parts of two laterally related eolian systems.

We dug a deeper trench pocket beneath the largest and lowermost gully on the upper slope to look for evidence of faulting. We found contiguous, unbroken, undeformed sand dune strata.

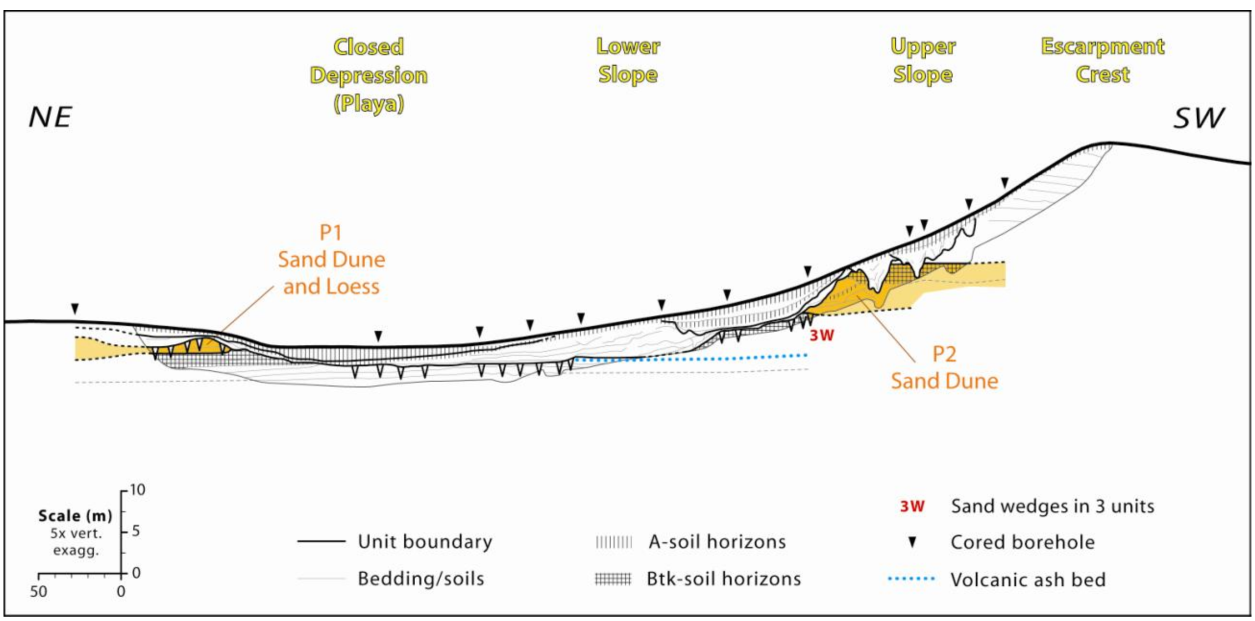

Figure 12. Cross-section of the Anton escarpment study site showing late Pleistocene sand dune and loess sediments, units P1 and P2, from the trench (brighter orange) and cores (light orange).

Units P3, P4, and P5. A complex array of interrelated eolian, periglacial, and erosional-infill deposits of late Pleistocene (latest glacial maximum) age is found throughout the trench. In our estimation, these units mark the appearance of the Anton escarpment as a major geomorphic feature. We will introduce these units using **Figure 13** to illustrate the great degree of lateral variability.

Unit P3 consists of massive loess (7 m), overlain by sand sheet (4 m) and loess (4 m) deposits. The basal contact is nearly flat and is marked by a cumlic soil (a diffuse, humic Bw horizon where soil formation and sediment accumulation are approximately equal). The internal bedding dips westward at low angles, ranging from 1º at the base of the sand sheet to 4º near the escarpment crest. The age of the unit is 29 to approximately 16 ka, based on luminescence dating.

Unit P4 is located at the base of the upper escarpment slope. It has a channel-shaped base that is eroded 3.5 m into the underlying sediments and is filled with silt and sand. We interpret it to be a gully fill deposit. We originally considered this feature to be Holocene; retrenching allowed us to recover three samples for luminescence age-dating that returned consistent dates of ca 18.2 ka. Detailed logging of the gully revealed that the fill is mostly windblown or locally sheet-washed silt. Water-deposited sand bodies in cut-and-fill structures comprise less than 5% of the unit.

Unit P5 is a laterally extensive, internally complex deposit. The basal contact is a well-defined erosion surface (previously described) that has 12 m of relief. The erosion surface is step-like in profile. It is roughly flat-lying where it overlies resistant calcic paleosols in older units. It is steeper (paleo walls of up to 15º) in other places where it cuts less-resistant, older units. Overall, the surface forms a series of flat to bowl-shaped depressions that represent an ancient, erosional paleotopography.

The oldest P5 sediments are sand wedges. These periglacial features formed in the underlying sediments (from seasonal thermal contraction of the ground under permafrost conditions) and exhibit vertical

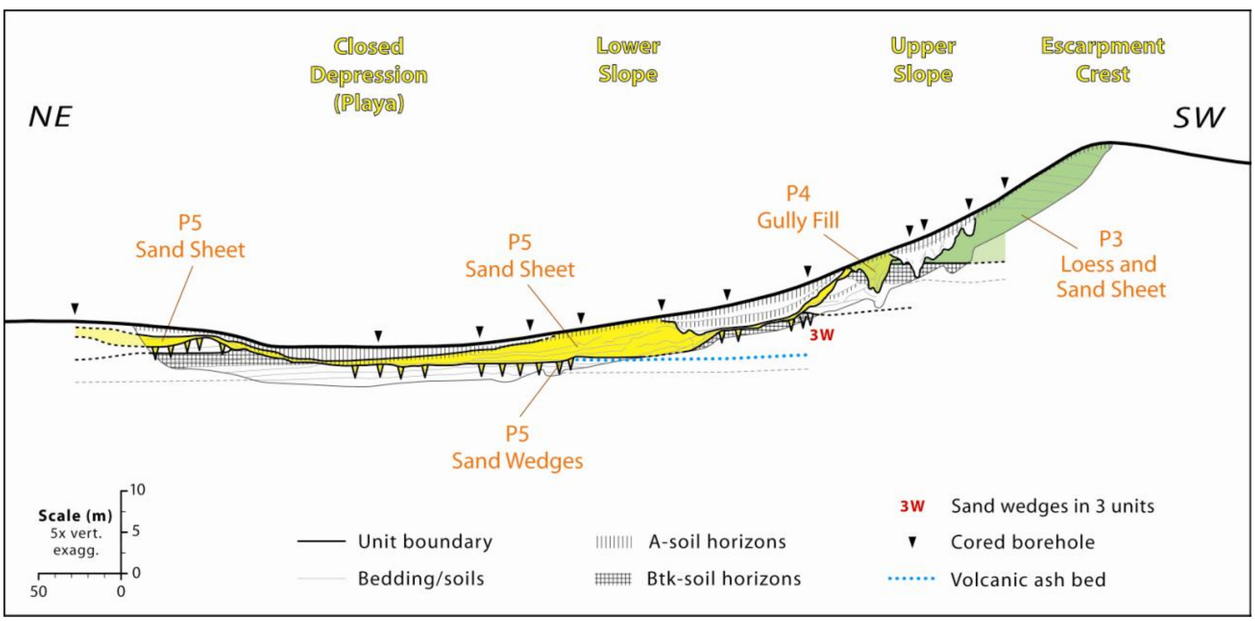

Figure 13. Cross-section of the Anton escarpment study site showing late Pleistocene sand sheet, sand wedge, gully fill, and loess sediments, units P3, P4, and P5, from the trench (brighter yellow, yellow-green, and green) and cores (dull yellow and green).

laminations of fine sand to granules. We logged over 90 sand wedges in the southwestern wall of the trenches. Seen from above, they have polygonal patterns. They are up to 2 m long in vertical dimension, similar to modern sand wedges (Murton, 2007). We interpret that the ground surface during the time of sand-wedge deposition must have been close to or slightly above the existing basal erosion surface. Luminescence dating of five sand wedges yielded ages of 27.5 to 18 ka. This is the youngest of three levels of sand wedges (labeled 3W in **Figure 13**).

The lowest sediments that immediately overlie the sand wedges and erosion surface consist of up to 0.5 m of clayey silt to granule-bearing sand, all of which show evidence of frost heave and cracking. These sediments are 19.5 to 16.5 ka in age, based on sediment luminescence dates and radiocarbon dating of a camel humerus recovered from the sediments.

Most of unit P5 contains sand sheet deposits that drape the paleotopography and partially fill the erosional depressions. These deposits are up to 5 m thick. They consist of thinly interbedded sand and silt layers and abundant mound-like forms that we interpret to be shrub coppice dunes. The strata are more silt-rich and flat-lying within the lowest erosional depression, coincident with the modern playa. The sand sheet deposits range from ca. 16.5 to 12.5 ka in age, based on luminescence dating.

Units P3, P4, and P5 are overlapping in age. However, they occupy different parts of the escarpment, occur at different elevations, and contain mutually exclusive facies assemblages. In **Figure 14**, we show how these units are related through time by dividing them into three age-specific stages.

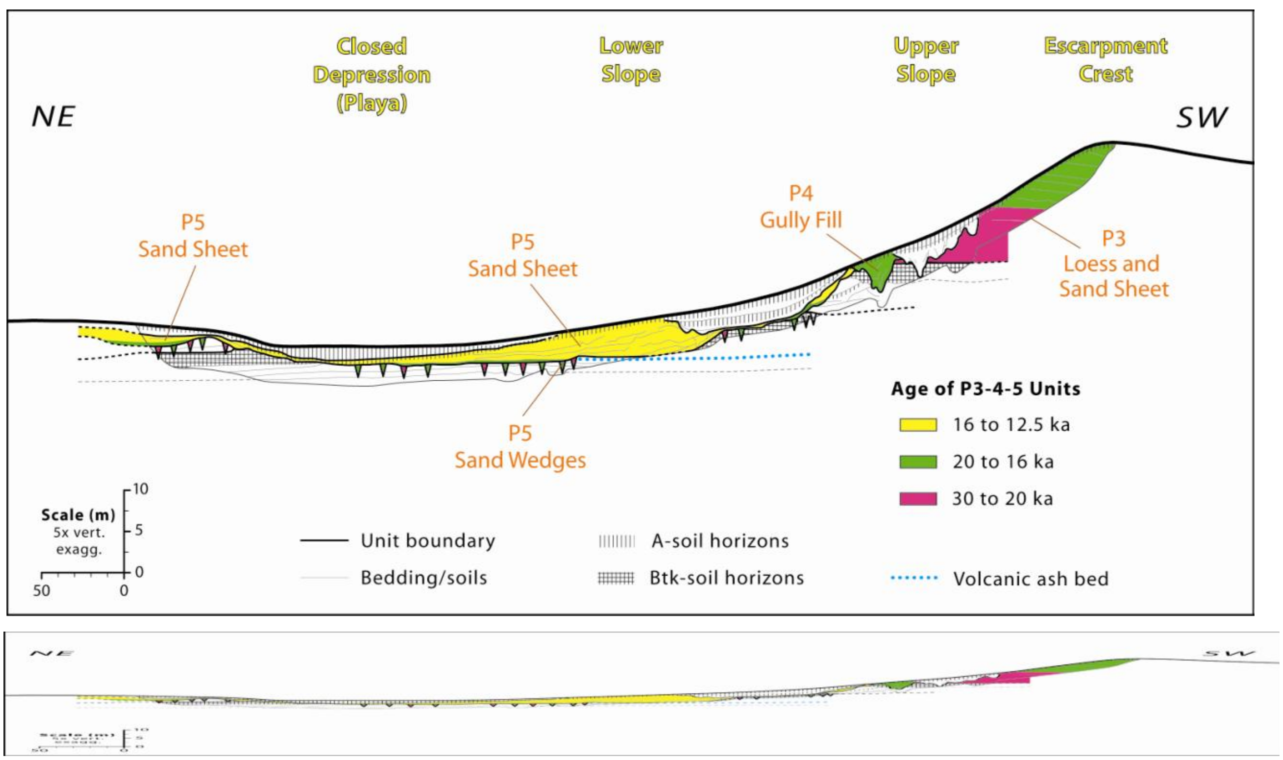

Figure 14. Cross-section of the Anton escarpment study site showing units P3, P4, and P5 broken into three different depositional stages. This is shown at 5x (top) and 1x (bottom) vertical exaggerations. We interpret that the escarpment formed during 30 to 20 ka, reached its maximum topographic height during 20 to 16 ka, and was partially infilled during 16 to 12.5 ka.

The first stage (ca. 30 to 20 ka) is represented by the 7-m thick, massive loess in the upper slope and the basal sand wedges in the lower slope and playa areas. The loess has a transitional base and no apparent internal stratigraphic breaks, which indicate uninterrupted aggradation. In contrast, the sand wedges occupy erosional benches that are 6 to 12 m lower than the base of the loess. We interpret this to be the first appearance of the Anton escarpment as a geomorphic feature. It was a consequence of active deposition in the west and adjacent, active erosion in the east under periglacial (permafrost) conditions. The flat-bottomed nature of the erosion surface, along with the absence of fluvial lithofacies, indicates that wind was the agent of erosion. At the end of this stage, 7 m of loess aggraded in the west and there was 19 m of topographic relief on the escarpment.

The second stage (ca. 20 to 16 ka) featured similar processes. Sand sheet and loess deposits (8 m total thickness) aggraded in the west. The erosion surface in the east was maintained and more periglacial sand wedges formed. An episode of escarpment-face erosion is indicated by the 16.2 ka filled gully on the upper slope. This roughly coincides with the deposition of thin, clayey silt in the lowest part of the erosional depression to the east. Those sediments may be playa deposits at the distal end of a local gully and alluvial fan system. At the end of this stage there was 27 m of topographic relief, which represents the maximum topographic relief developed on the escarpment.

The third stage (ca. 16 to 12.5 ka) shows a change in terms of processes and deposition. Deposition on the loess plateau in the west apparently ceased. In contrast, up to 5 m sand sheet deposits aggraded in the east, partially filling the erosional depression and blanketing the low-lying topography. This resulted in a smoother escarpment slope, and the topographic relief was reduced by several meters.

Units H1, H2, and H3. The escarpment and flanking areas were locally modified during the very latest Pleistocene and Holocene. **Figure 15** shows three near-surface deposits of mostly Holocene age. Unit H1 consists of loess that fills a flat-bottomed (eolian-deflation) depression on the lower escarpment slope. This deposit contains a humic, buried A-soil horizon. We tentatively identify this as the Brady soil, a widely recognized paleosol around the western Great Plains. A second H1 loess deposit drapes the low knob to the northeast of the playa.

Unit H2 consists of poorly stratified, rodent-burrowed silt and sand in the upper slope. It fills a series of overlapping channels with erosional bases and is interpreted to be a complex of filled gullies.

Unit H3 consists of a very dark, organic- and clay-rich, silty verisol (A-soil horizon) that occupies the modern playa depression. Age dates for units H1, H2, and H3 range from 12.5 to 6.4 ka from radiocarbon and luminescence dating.

There is potentially a thin wedge of Holocene loess at the escarpment crest where a single luminescence age of 3.2 ka was obtained. The other possibility is that the soil sample is late Pleistocene in age but was affected by modern pedogenic processes, resulting in a too-young age. We do not see other stratigraphic evidence to support the presence of Holocene loess at the escarpment crest.

The Holocene units are generally thin (less than 3 m thick) and either fill local depressions or form thin drapes on pre-existing topography. The evidence shows that the processes that operated during the Holocene (e.g., eolian deflation and erosion, gullying, loess and slope-runoff deposition, soil formation) were similar to those of the late Pleistocene. The main differences are (a) no evidence of periglacial processes; (b) humic rather than calcic paleosols; and (c) lesser magnitude of Holocene erosion and deposition. We interpret that the escarpment was already fully formed during the Holocene.

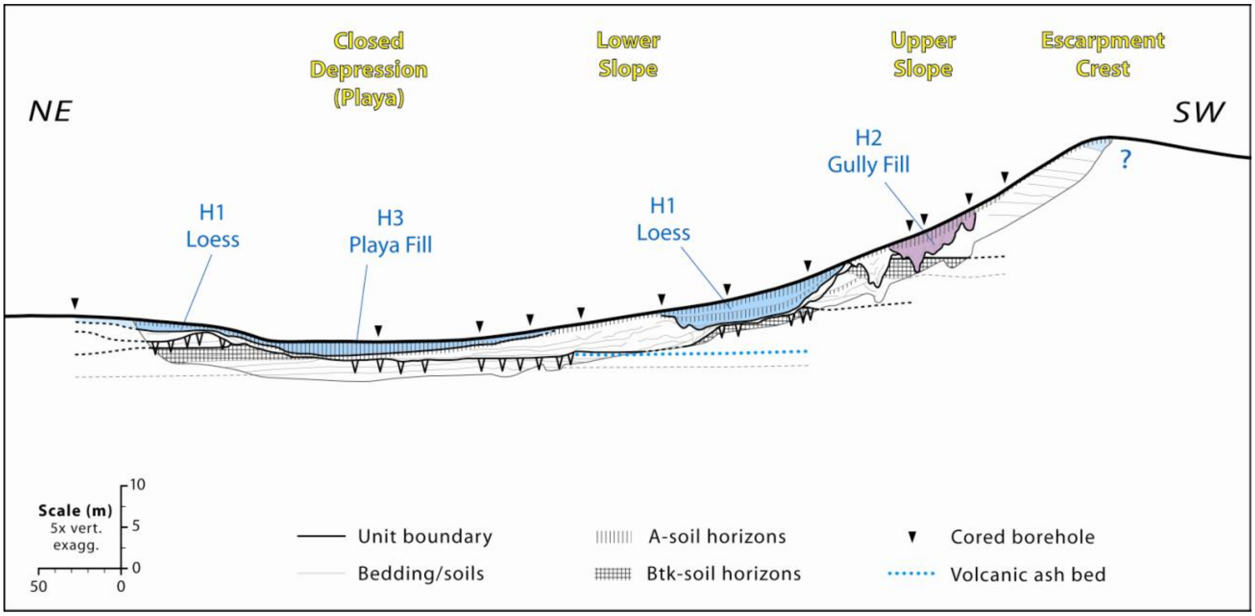

Figure 15. Cross-section of the Anton escarpment study site showing latest Pleistocene and Holocene loess, playa, and gully fill sediments, units P3, P4, and P5, from the trench (brighter blue) and cores (dull blue).

<u>Discussion of Results and Seismic Hazard</u>

Our investigations under this NEHRP grant show that the late Quaternary sediments that underlie the escarpment crest, slope, and adjacent lowlands are unfaulted and have not undergone seismic-related deformations. The escarpment itself is a result of combined wind erosion and deposition and formed from approximately 29 to 16 ka. Since then, the escarpment slope experienced modest erosion. The adjacent lowlands experienced periods of deflation and erosion followed by infilling.

We are working on a regional model that explains the escarpment in relation to paleowinds and potential sediment sources and sinks. The escarpment marks a geomorphic and topographic boundary between a loess plateau and a sand-swept lowland (as shown in **Figure 3**). The loess plateau is downwind from the Fort Morgan area, where extensive sand-dune fields aggraded south of the South Platte River. It appears that the sand rarely migrated onto the High Plains during the late Pleistocene and Holocene. Dust blew past the dune field and onto the High Plains, and the loess plateau aggraded in a largely sand-free environment.

In contrast, the lowland contains abundant sand-dune fields of Holocene age. There are scattered, patchy, partially eroded remnants of late Pleistocene loess deposits. It appears that the sand can migrate from the South Platte River and onto the High Plains between Brush and Sterling. We interpret that migrating sand dunes and sand sheets either (a) prevented loess from accumulating or (b) partially or fully eroded loess deposited during the late Pleistocene. (Interestingly, late Pleistocene loess plateaus are found immediately downwind of this sand-migration "fairway.")

Because the Anton escarpment is of non-tectonic, eolian origin, there is no apparent seismic hazard associated with this geomorphic feature. Machette and others (1998) had similar findings for the Ord escarpment in central Nebraska. There are many smaller, northwest-southeast trending escarpments on

Colorado's High Plains that resemble the Anton escarpment and have possible wind-related origins. Such features may cover or mask faults; this is a consideration for assessing potentially tectonic features in this region.

<u>Other Scientific Discoveries</u>

CGS' investigations at the Anton site yielded many exciting scientific discoveries. The trenches exposed an unprecedented section of Quaternary deposits, perhaps one of the best exposures in the High Plains. Many scientists visited the trenches during the course of our investigations. We benefitted from on-site discussions with experts in paleoseismology, Quaternary geology, geomorphology, archaeology, soil science, paleontology, and paleoclimate. The following is a listing of findings that are of particular interest to these scientists and to the scientific community:

Detailed trench logs and over 60 radiocarbon and luminescence age dates allowed us to create a high-resolution stratigraphic framework and, subsequently, a depositional and escarpment-evolution story that adds significantly to previous work and may be applicable for other areas in the Great Plains region.

We found evidence for three distinct periods of permafrost, as evidenced by polygonal sand wedges and other periglacial features. Such features are well documented to the north, in Wyoming. However, no sand wedges were previously described in the literature as occurring on the Colorado Plains. The Anton site is well south of the postulated, late Pleistocene occurrence of permafrost (Péwé, 1983). Our findings have ramifications with regard to paleoclimate: the sand wedges indicate that the Colorado Plains were much colder during Pleistocene glaciations than was previously recognized.

The trenches yielded specimens of archaeological and paleontological interest (**Figure 16**). We found a broken spear point and scraper in the basal Brady soil (in unit H1, dated at ca 12.5 ka). These artifacts are interpreted to be from the Clovis culture, and this becomes the sixth recognized Clovis site in Colorado. We found scattered camel, horse, and bison bones ranging from Pliocene to late Pleistocene in age. One specimen of particular interest, a camel humerus, displays sharp fractures and apparent percussion marks. Dated at >16.5 ka, this specimen may harbor evidence for pre-Clovis peopling of North America. The archaeological significance of the Anton site is presented in Holen and Noe (2006).

Figure 16. Clovis lithic artifacts (left) and pre-Clovis, fractured camel humerus (right) found in the Anton trenches.

DISSEMINATION OF RESULTS

Peer Field Review

CGS hosted a peer-review event for USGS personnel at the Anton study site on November 11, 2007. In attendance were Tony Crone, Rus Wheeler, Steve Personius, and Dan Muhs. We toured the trenches and presented our findings to the group. These paleoseismology experts concurred with our basic findings (i.e., that the escarpment is an erosional and non-tectonic feature).

Publications In Progress

Work is beginning on two papers for submittal to peer-reviewed journals. One paper addresses the overall investigation and results, the lack of evidence for young faulting, and our interpreting the escarpment as a mixed wind-deposition and wind-erosion feature. The other paper focuses on the discovery of polygonal, periglacial sand wedges at three different stratigraphic intervals in the trenches. It will be the first published evidence of extreme and recurring permafrost conditions on Colorado's Great Plains during the Pleistocene.

David Noe, CGS project P.I., is the primary author for these papers. Co-authors include Alan Busacca and Steven Forman, who worked on the project as contractors. We have not yet determined which journals to submit the papers. CGS has internal funding to cover this work.

Outreach

The preliminary results were published as an abstract and presented as a poster at the annual meeting of the Association of Environmental and Engineering Geologists (AEG) in New Orleans, September 15-18, 2008 (Noe and others, 2008). A modified version of that abstract is used as the abstract for this final grant report.

CGS intends to convey our findings to practitioners and the public. In particular, presentations could be given to groups such as USGS Earthquake Hazards Group, Geological Society of America, Association of Environmental and Engineering Geologists, Colorado Scientific Society, and Colorado Earthquake Hazards Mitigation Council. In addition, we intend to work with local officials (particularly County Commissioners and the state and county offices of emergency management) to find appropriate venues for the dissemination of our findings. CGS has internal funding to promote follow-up outreach work.

Availability of Project Data

The detailed trench logs for all four trenches are included as digital appendices as part of the final report. Additional copies of these documents may be requested from the project primary investigator, David C. Noe, at Colorado Geological Survey. The contact information is shown on the cover page of this report.

APPENDICES

The following .pdf files accompany the report. They are the four detailed trench logs. The upper (4004) and lower (2005) trench logs were made before the current project. The center and playa (2007) trench logs were made during the course of NEHRP grant 07HQGR0090.

- 07HQGR0090 – anton 2004 upper trench log.pdf
- 07HQGR0090 – anton 2005 lower trench log.pdf
- 07HQGR0090 – anton 2007 center trench log.pdf
- 07HQGR0090 – anton 2007 playa trench log.pdf

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